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FINAL REPORT ON MICROWAVE PORTION OF THE OXYGEN LINES REFRACTOMETER

JUNE 1966

R. J. Snay

Prepared for

DIRECTORATE OF AEROSPACE INSTRUMENTATION

ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts



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Project 705A

Prepared by

THE MITRE CORPORATION
Bedford, Massachusetts
Contract AF19(628)-5165

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ABSTRACT

A microwave subsystem was installed in The MITRE Corporation's refractometer vans as an integral part of the oxygen-lines refractometer. In operation, two coherent frequencies, 45 and 90 Gc, are transmitted along a 23-km path, and the change in differential phase shift is measured at the receiver. This change is an indication of the refractive qualities of the atmosphere over the path. The equipment was tested at a field site in the Lake Winnepesaukee, New Hampshire, region; test results and recommendations for improving system sensitivity and stability are given.

REVIEW AND APPROVAL

Publication of this technical report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



C. V. HORRIGAN
Acting Director
Aerospace Instrumentation

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SECTION I

INTRODUCTION

The purpose of the oxygen lines refractometer is to determine the refractive qualities of the atmosphere between a transmitter and receiver. The average refractive index is determined by measurement of the transit time, ΔT , of two frequencies over a path length, L . If two coherent frequencies are transmitted, the dispersive refractivity (change in refractivity versus frequency) will change the relative phases of the two signals propagating over the same path. Thus, ^[1]*

$$c (\Delta T_1 - \Delta T_2) = \int_0^L [N_1(\ell) - N_2(\ell)] d\ell, \quad (1)$$

where

ΔT_1 = the transit time of frequency f_1 ,

ΔT_2 = the transit time of frequency f_2 ,

$N_1(\ell)$ = the refractivity (n-1) of frequency f_1 ,

$N_2(\ell)$ = the refractivity (n-2) of frequency f_2 ,

n = the local index of refraction (c/v),

c = the velocity of light, and

v = the local phase velocity.

*Numbers in brackets denote references cited at the end of this report.

The quantity in the brackets is called the dispersivity. In terms of the electrical path length, φ is expressed in radians as $\varphi = \beta L$, where $\beta = \omega/v$ is the phase constant.

Then

$$\varphi = \frac{\omega L}{v} = \omega \Delta T \text{ or } \Delta T_1 = \frac{\varphi_1}{\omega_1}, \Delta T_2 = \frac{\varphi_2}{\omega_2}. \quad (2)$$

Substituting Equation (2) into Equation (1),

$$\frac{c}{2\pi f_2} \left(\frac{f_2 \varphi_1}{f_1} - \varphi_2 \right) = \int_0^L [N_1(\ell) - N_2(\ell)] d\ell. \quad (3)$$

Equation (3) shows that the line integral of the dispersivity multiplied by a constant equals the differential phase $\left[\left(f_2/f_1 \right) \varphi_1 - \varphi_2 \right]$. In terms of the oxygen lines refractometer, f_2 is the second harmonic of f_1 and the ratio f_2/f_1 is 2. The frequencies f_1 and f_2 are chosen to bracket the oxygen molecular absorption lines grouped around 5 mm (60 Gc); in this system, these frequencies are 45 and 90 Gc. This selection was made because of the lower attenuation existing on either side of the oxygen absorption lines. Frequency-bracketing of the oxygen absorption lines assures a larger dispersivity than would be obtained by locating both frequencies on the same side of the absorption lines.

SECTION II

SYSTEM DESCRIPTION

TRANSMITTER

Figure 1 is a block diagram of the microwave portion of the oxygen-lines-integral-refractometer transmitter. Figure 2 shows the main transmitter with the original Varian tube, later replaced by a 3-watt, water-cooled OKI laddertron (Figure 3). The OKI laddertron is a single-cavity, multigap strip beam tube using permanent-magnet beam focusing. Figure 4 shows the operating characteristics versus cavity voltage of the laddertron. Typical tube operating voltages and currents at 45 Gc are as follows:

Heater voltage	6.3 volts
Heater current	1.3 amps
Cavity voltage	-1960 volts
Cathode current	135 ma
Grid voltage	-160 volts
Output power	3 watts

The output waveguide of the OKI laddertron is the standard RG-97/U waveguide (0.224-inch x 0.112-inch inside dimensions).

The laddertron 3-watt output, as shown in Figure 1, is fed into the main arm of a 20-db incident-power-monitor directional coupler. The auxiliary (coupled) arm of the directional coupler contains a frequency meter for frequency monitoring, and a variable attenuator and bolometer for power measurement. The main arm of the 20-db coupler is connected to a 10-db power splitter. The coupled arm of the power splitter contains a 45-Gc one-percent-bandwidth filter and a 45- to 90-Gc harmonic generator. The harmonic generator output enters the high-frequency arm of the double-ridge-wave guide frequency combiner. The principal arm of the power splitter

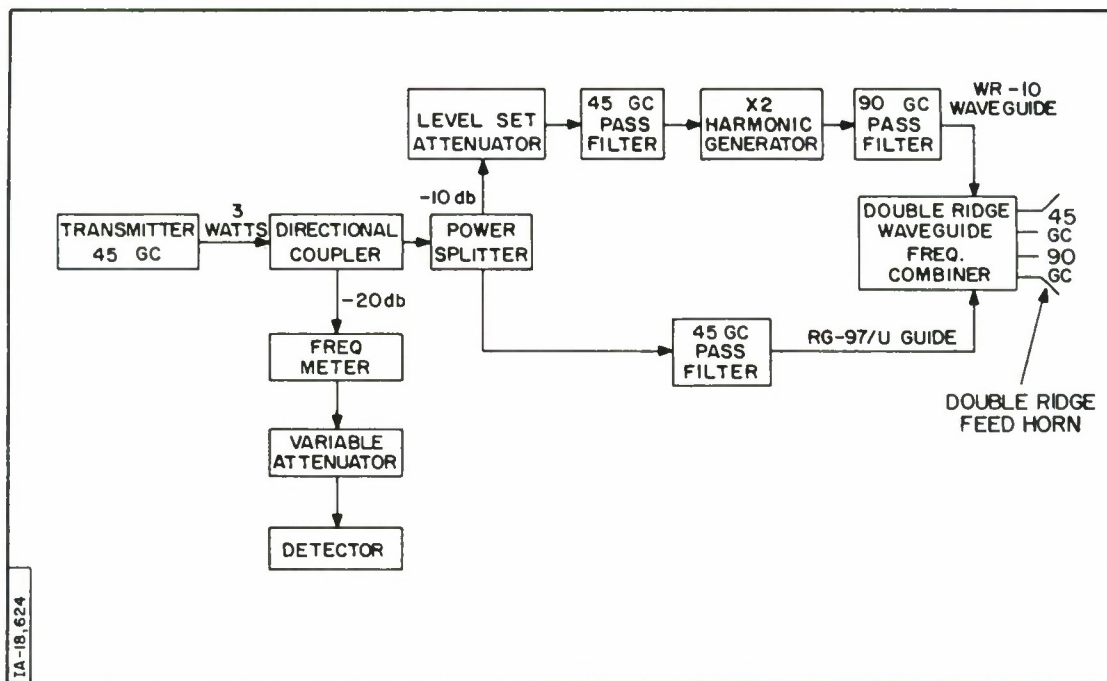


Figure 1. Oxygen Lines Refractometer Microwave Transmitter, Block Diagram

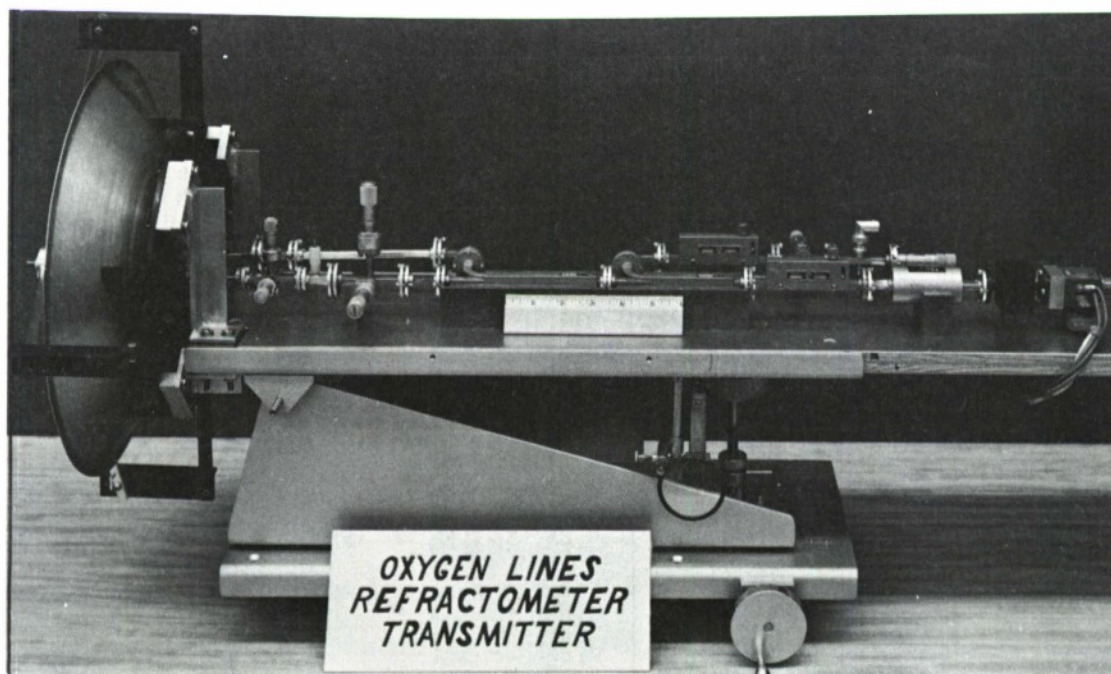


Figure 2. Oxygen Lines Refractometer Transmitter

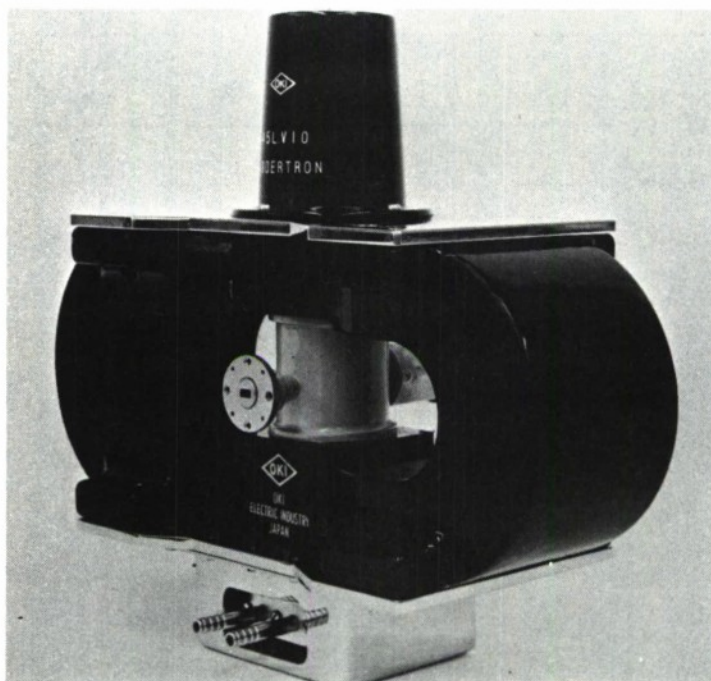


Figure 3. OKI 45-Gc Laddertron Tube

contains a 45-Gc one-percent bandpass filter and is connected to the low-frequency arm of the frequency combiner. A double-ridge tapered feed horn at the output of the frequency combiner completes the RF transmitter.

RECEIVER (Figure 5)

Figure 6 is a block diagram of the microwave portion of oxygen-lines-integral-refractometer receiver. The receiver front end contains a feed horn and frequency splitter identical to the transmitter horn and frequency combiner. The 45- and 90-Gc signals are separated in the frequency splitter and fed directly to single-ended mixers. The 45-Gc mixer employs a IN53C mixer crystal in a standard RG-97/U crystal mount. The 90-Gc mixer is a Philco 1N2792 germanium millimeter-wave mixer diode, integrally mounted in a section of RG-98/U waveguide. A special adaptor was fabricated to

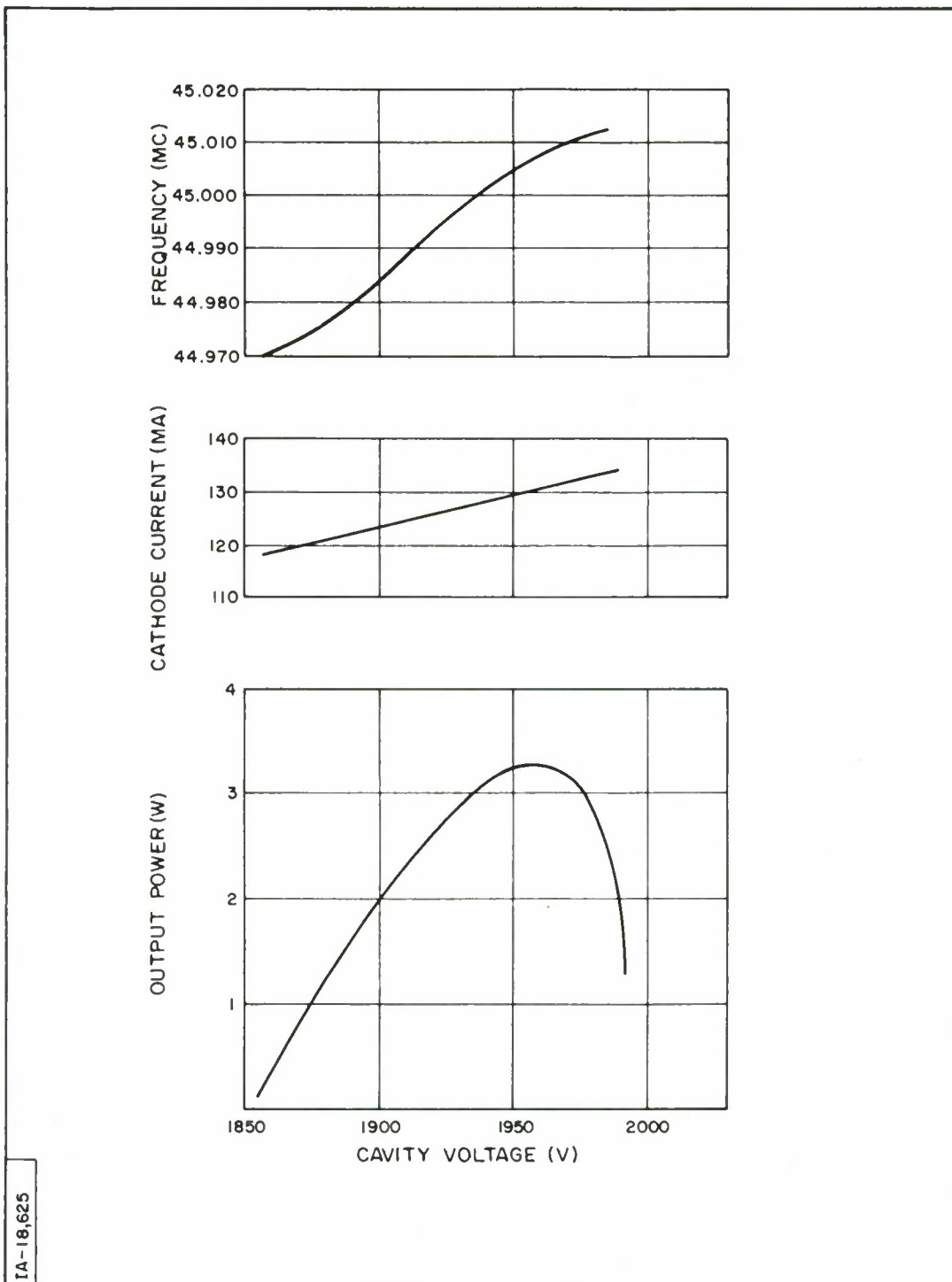


Figure 4. Operating Characteristics of an OKI 45-Gc Laddertron

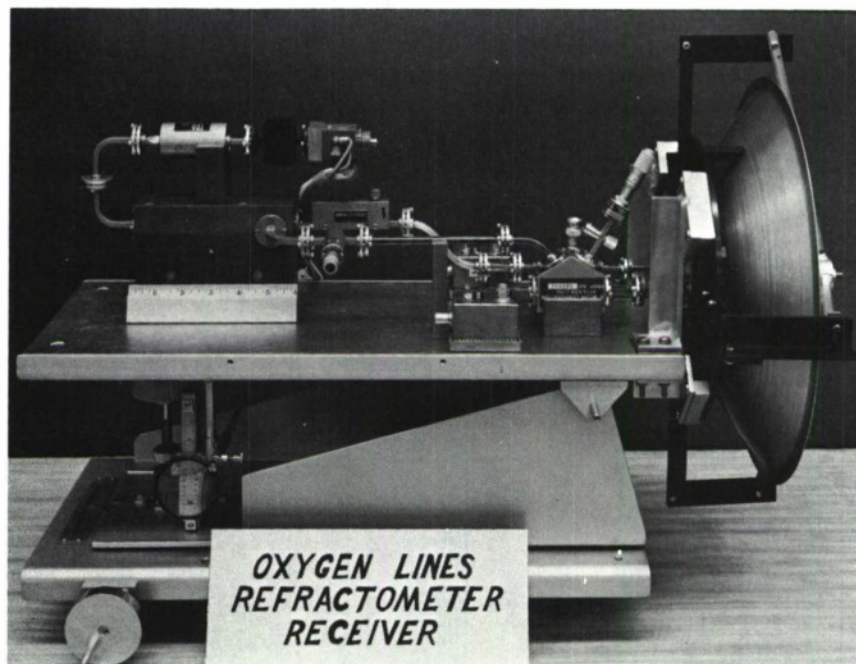


Figure 5. Oxygen Lines Refractometer Receiver

mate with the 90-Gc WR-10 waveguide. Harmonic mixing is used in the 90-Gc receiver channel. The common local-oscillator (LO) tube is a Varian VA250 reflex klystron operating at 250 kc above 45 Gc.

The receiver intermediate frequency (IF) is 250 kc. Automatic frequency control (AFC) is used to lock the LO klystron 250 kc from the transmitter frequency. The IF output of the 90-Gc mixer is 500 kc. An IF harmonic generator is employed to double the 250-kc IF in the 45-Gc mixer channel. These two 500-kc signals are then amplitude-limited and fed to a phase comparator that measures the relative phase difference between them. A minimum signal is required for the AFC to maintain a receiver lock-on to the transmitter. Table I lists the minimum lockable signal values of mixer-crystal current.

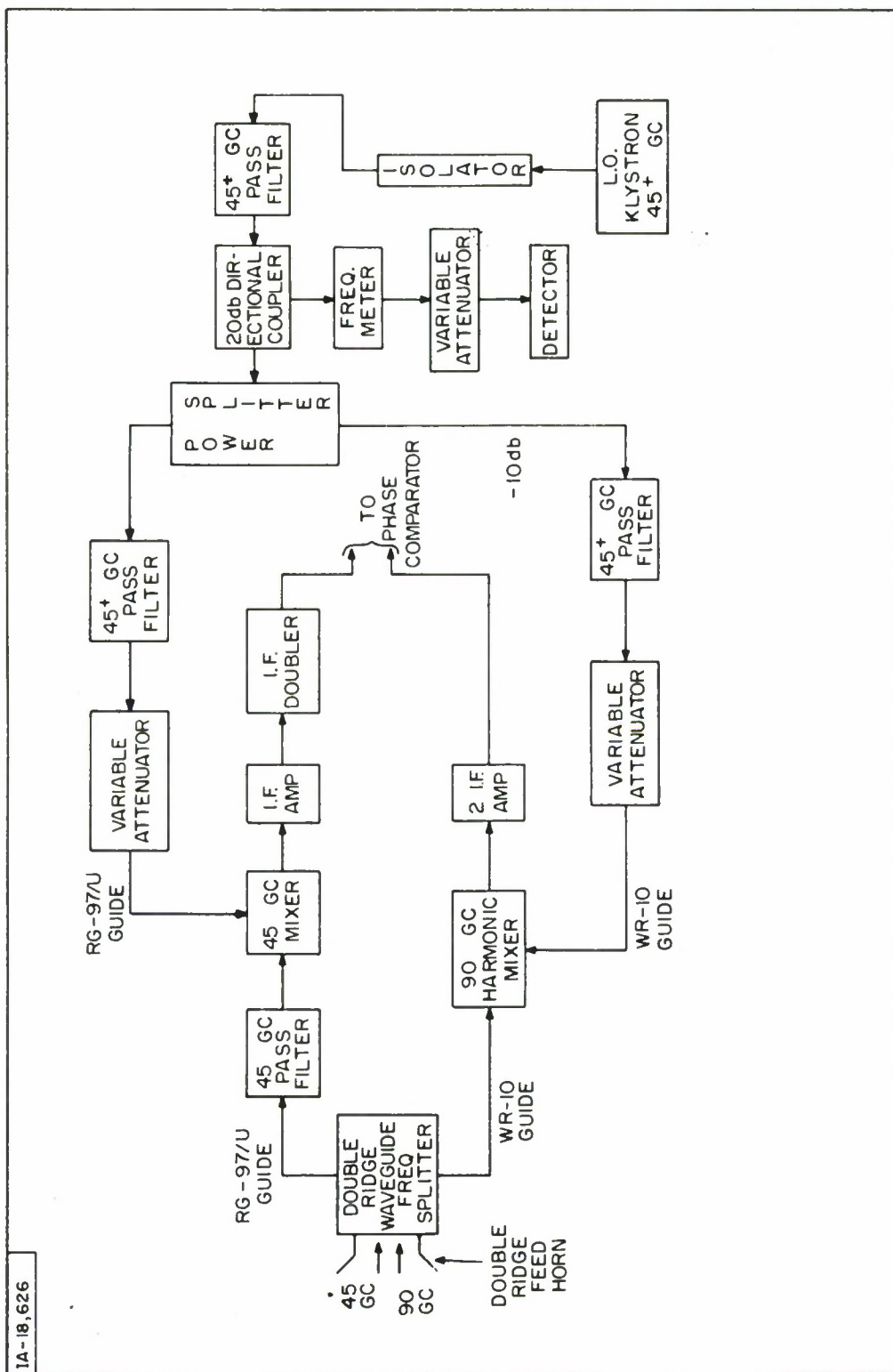


Figure 6. Oxygen Refractometer Microwave Receiver, Block Diagram

Table I
Minimum Lockable Signal Level

45-Gc Mixer Crystal Current (ma)	45-Gc Lock-On Sensitivity (dbm)
0.05	- 70
0.1	- 72
0.2	- 73
0.3	- 75
0.4	- 75
0.5	- 75
0.6	--

The test conditions for the data given in Table I are as follows:

- (a) intermediate frequency 258 kc ;
- (b) IF bandwidth 100 kc ;
- (c) crystal current changed by varying LO power ;
- (d) no external bias voltage on crystal ; and
- (e) RF attenuation inserted between transmitter and receiver.

REFERENCE TRANSMITTER

At the field test site, the main transmitter is located approximately 14 miles from the receiver. The reference transmitter at the receiver site provides a transmitting source for testing the complete receiver system; the reference transmitter is contained in a temperature-controlled box in the oxygen-lines-refractometer-receiver van. Because the reference transmitter is inside the receiver van, it provides a transmitting source independent of atmospheric changes and, thus it can be used to establish a differential phase reference in the receiver.

The reference transmitter is identical to the main transmitter except that it uses an ITT type F-2907 millimeter reflex klystron instead of an OKI laddertron. The dual-frequency output of the reference transmitter is fed directly to the cassegrain-reflector at the receiver, using a 45-degree splash plate (see Figure 7).

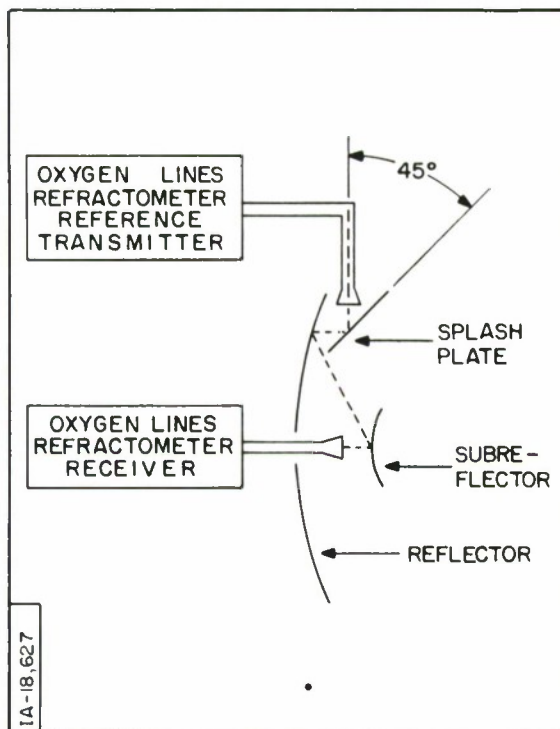


Figure 7. Reference Transmitter at Receiver Site

SECTION III

COMPONENT DESCRIPTION

FREQUENCY COMBINER

The frequency combiner (Figure 8) used in the main and reference transmitters is identical to the frequency splitter used in the receiver; i. e. , a double-ridge-waveguide symmetrical Y junction. The 45- and 90-Gc arms of the Y contain rectangular (0.225-inch x 0.112-inch at 45 Gc; 0.100-inch x 0.050-inch at 90 Gc) to double-ridge-waveguide transitions. The third arm of the Y remains in double-ridge-waveguide and supports the double-ridge feed horn. The dimensions and electrical characteristics of the double-ridge waveguide are shown in Figure 9.



Figure 8. Double-Ridge Waveguide
Frequency Combiner

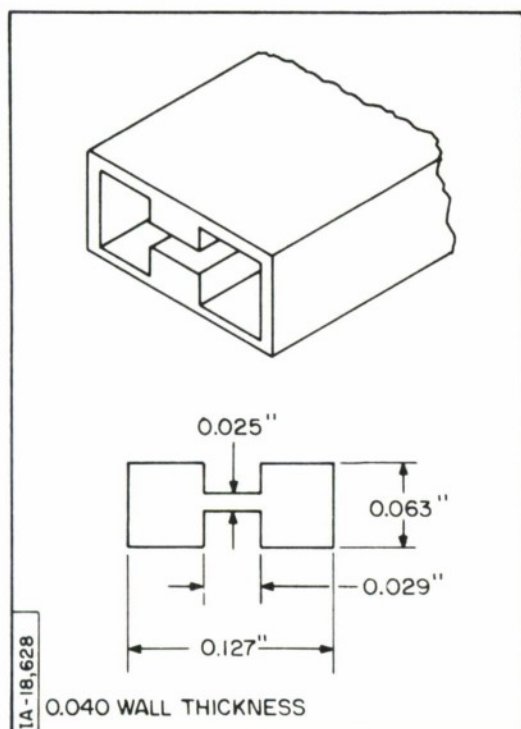


Figure 9. Oxygen Lines Double-Ridge Waveguide

The electrical characteristics of the double-ridge waveguide are shown in Table II.

Table II
Electrical Characteristics of Double-Ridge Waveguide

TE ₁₀ mode cutoff frequency	38 Gc
TE ₁₀ mode cutoff wavelength	0.308 inch
TE ₂₀ mode cutoff frequency	100 Gc
Characteristic impedance at 45 Gc	310 ohms
Characteristic impedance at 90 Gc	179 ohms
Theoretical bandwidth	$3.1 \left(\lambda_{c10} / \lambda_{c20} \right)$
Guide wavelength at 45 Gc	0.502 inch
Guide wavelength at 90 Gc	0.145 inch

The dimensions of the double-ridge waveguide were obtained from an IBM 7030 computer program, Ridge I, written at The MITRE Corporation,^[6] using equations from Cohn,^[2] Chen,^[3] and Hopfer.^[4] These dimensions were so chosen that 45 Gc is approximately the same number of megacycles above the TE_{10} -mode cutoff frequency (7 mc) as 90 Gc is below the TE_{20} -mode cutoff frequency (10 mc). The VSWR of the double-ridge Y splitter is 1.3 at 45 Gc and 1.25 at 90 Gc.

HARMONIC GENERATOR

Figure 10 shows the oxygen-lines-refractometer harmonic generator. This harmonic generator is an inline type fabricated with the fundamental-frequency waveguide, the nonlinear element, and the harmonic-frequency waveguide all on the same longitudinal axis. In a crossguide type (Figure 11), the harmonic-frequency waveguide is mounted on top of the fundamental-frequency guide, and turned 90 degrees away from the mainline longitudinal axis. The nonlinear element (diode) is mounted on a vertical axis through the broad walls of both waveguides, and an adjustable short circuit is located in each waveguide for input and output tuning.

The nonlinear element used in the oxygen-lines harmonic generator is a gallium-arsenide microstick varactor diode (see Figure 12); Table III lists the electrical characteristics of a typical microstick varactor.

The impedance of a microstick varactor mounted in the inline harmonic generator was measured at 45 Gc as a function of fixed d-c bias voltage and plotted (see Figure 13). From this plot, the quality factor or Q of the varactor

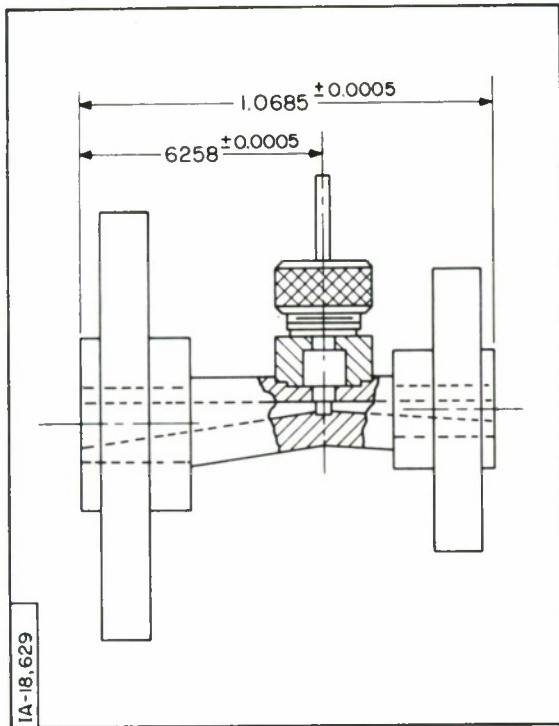


Figure 10. 45- to 90-Gc Harmonic Generator

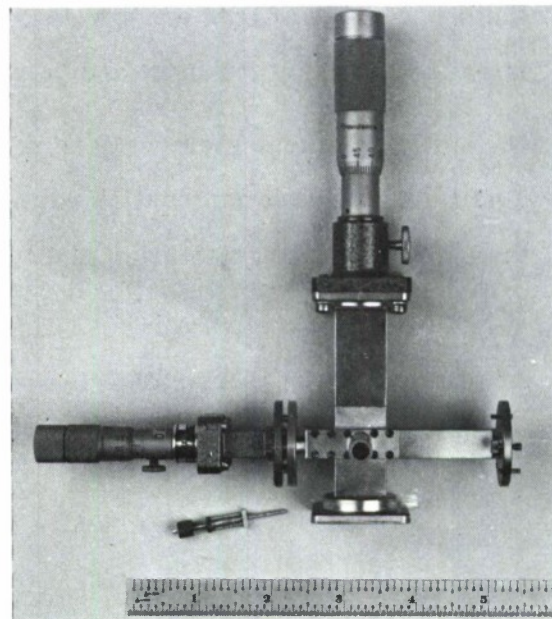


Figure 11. 15- to 45-Gc Harmonic Tripler

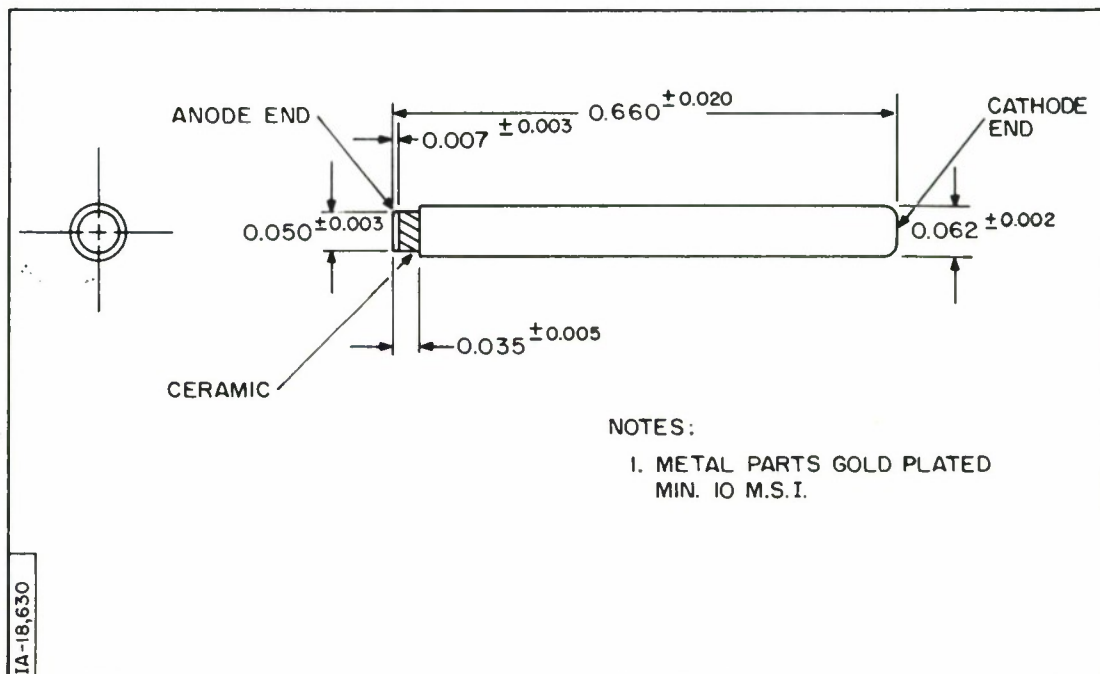


Figure 12. Microstick Varactor Diode

Table III

Electrical Characteristics of Varactor Diode

Junction capacitance at 0 volts (C_{j0})	=	0.20 pf
Junction capacitance at -6 volts (C_{j-6})	=	0.08 pf
Junction capacitance at breakdown (C_{jVB})	=	0.05 pf
Breakdown voltage (V_B)	=	30 volts
Cutoff frequency at -6 volts (f_{c-6})	=	200 Gc

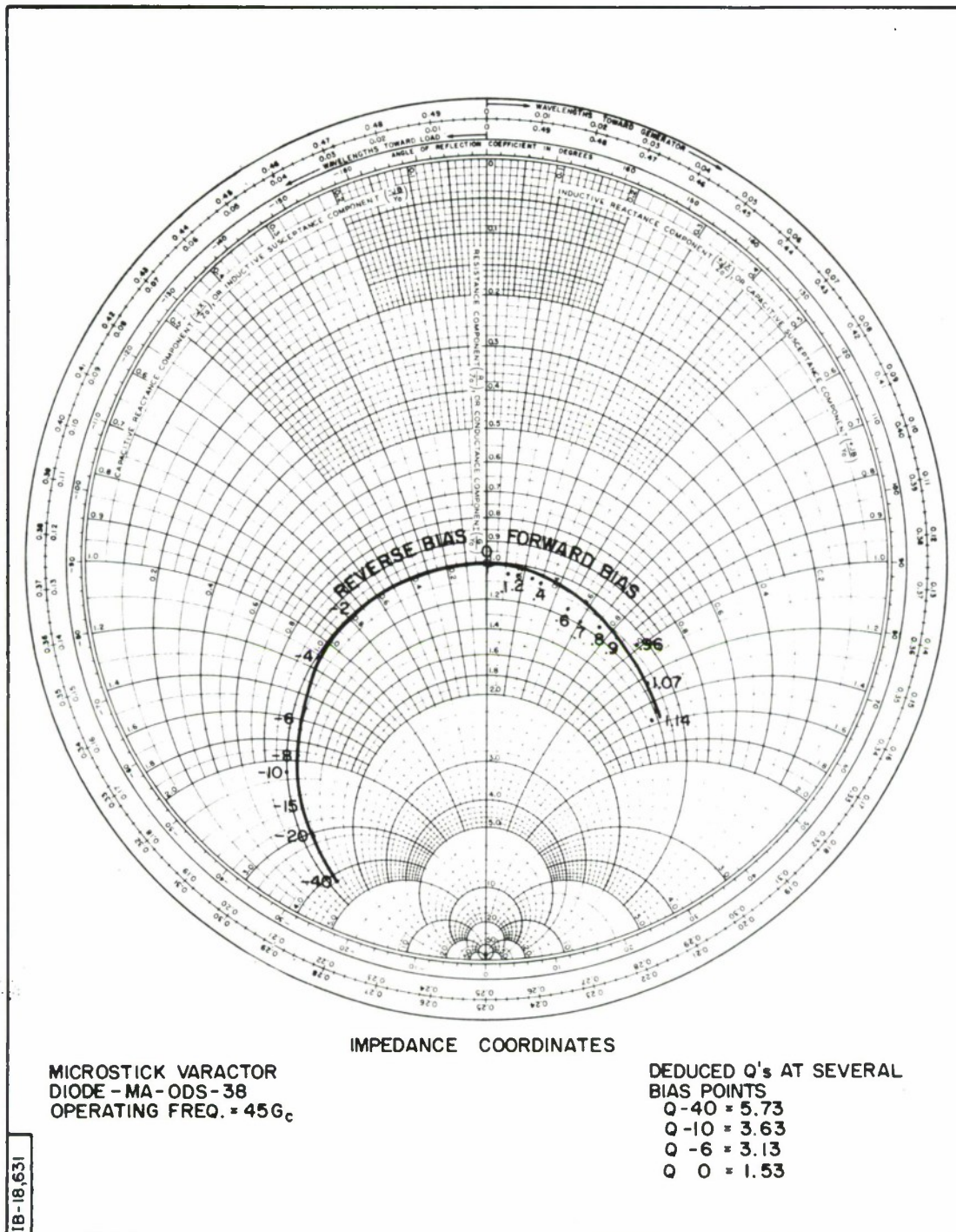


Figure 13. Impedance of Varactor and Holder at 45 Gc

can be deduced for any bias voltage.^[5] For example, the deduced Q at several different bias voltage is as follows:

<u>Bias Voltage</u>	<u>Deduced Q</u>
0	1.53
-6	3.13
-10	3.63
-40	5.73

The figure of merit, f_c , for a varactor diode can be calculated from the deduced Q:

$$f_c = Q_{-40} f_o ;$$

where f_o is the operating frequency in Gc, and Q_{-40} is the deduced Q at -40 volts bias,

$$\begin{aligned} f_c &= (5.73) (45) \\ &= 258 \text{ Gc} . \end{aligned}$$

In the oxygen-lines refractometer, the harmonic generator is preceeded by a 45-Gc E-H tuner and followed by a 90-Gc E-H tuner. The 45-Gc input tuner is adjusted for minimum reflected power from the generator at 45 Gc, and the 90-Gc output tuner is set for maximum second-harmonic power. The E-H tuners employ noncontacting bucket shorts and contribute very little loss to the system. The 45-Gc input filter (Figure 1) is experimentally positioned to reflect the 90-Gc signal in the proper phase to enhance the second-harmonic signal. The 90-Gc output filter (Figure 1) is a 45- to 90-Gc rectangular waveguide taper which is beyond cutoff to the 45-Gc signal. The length of the taper is electrically adjustable by a capacitive tuning screw in the tapered section; this adjustment also provides for maximizing the second-harmonic

signal. Self-bias was used in this application because the results of the water-line refractometer system^[1] indicated improved phase stability as a function of input-power fluctuations when the varactor is self-biased. Correct adjustment of the input and output tuners results in an efficiency of approximately three percent at an incident-power level of 70 to 200 milliwatts. Above 200-mw incident power, the diode efficiency deteriorated rapidly. Diode burnout occurred at an incident-power level of 400 mw. The main transmitter harmonic generator results are listed in Table IV.

Table IV
Main Transmitter Harmonic Generator Characteristics
(Diode No. 45; Diffusion No. GA25)

Capacitance at 0 volts (C_0)	= 0.22 pf
Capacitance at -6 volts (C_{-6})	= 0.09 pf
Capacitance at Breakdown (C_{VB})	= 0.06 pf
Cutoff frequency at -6 volts (f_{c-6})	= 240 Gc
Power input (P_{in}) at 45 Gc	= 100 mw
Power output (P_{out}) at 90 Gc	= 2.8 mw
Bias Resistance (R)	= 40 k ohms
Breakdown Voltage (V_B)	= -23 volts

FILTERS

A five-section Q-band filter (Figure 14), (0.224-inch x 0.112-inch waveguide), with a center frequency of 45 Gc and a one-percent bandwidth^[7] and

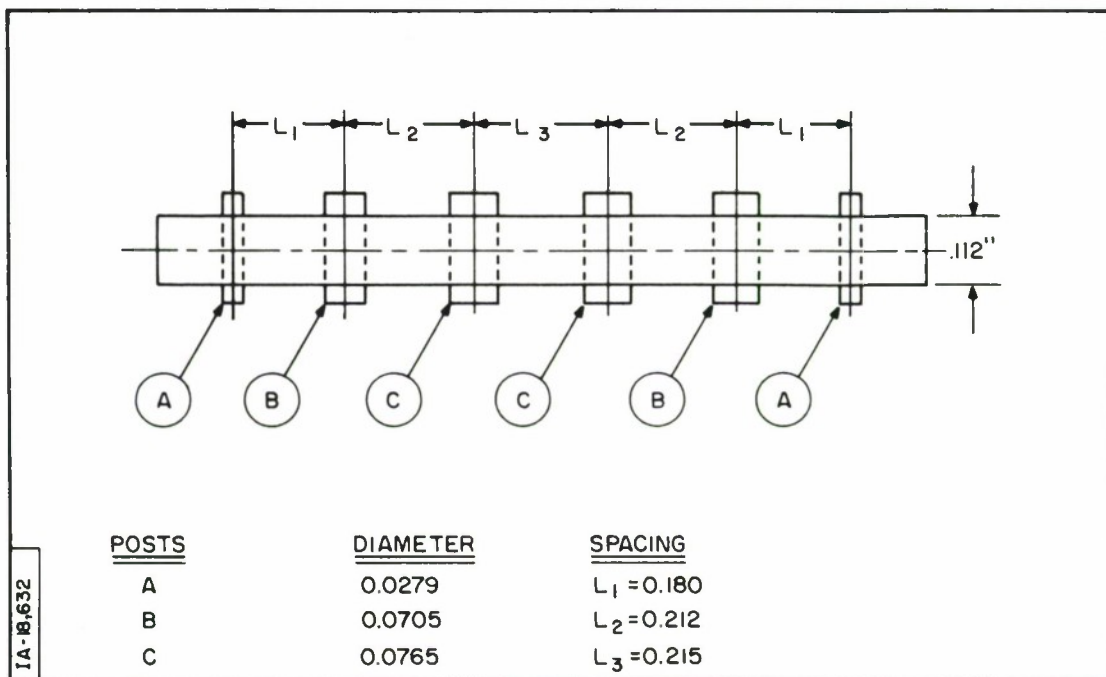


Figure 14. Inductive Post Filter for 0.224-inch x 0.112-inch Waveguide

employing centered inductive posts in a rectangular waveguide, was designed with the aid of an IBM 7030 computer program.^[8] A plot of VSWR and insertion loss versus frequency is shown in Figure 15.

MIXERS

45-Gc Mixer

The 45-Gc mixer shown in Figure 1 employs a 1N53C mixer crystal in a standard Q-band detector mount. A waveguide triple-stub tuner is placed in front of the detector mount and adjusted for best RF impedance match (less than 1.2:1) at 45 Gc.

90-Gc Mixer

Harmonic mixing is used in the 90-Gc channel of the refractometer, thus avoiding the requirement for a 45- to 90-Gc harmonic generator at the

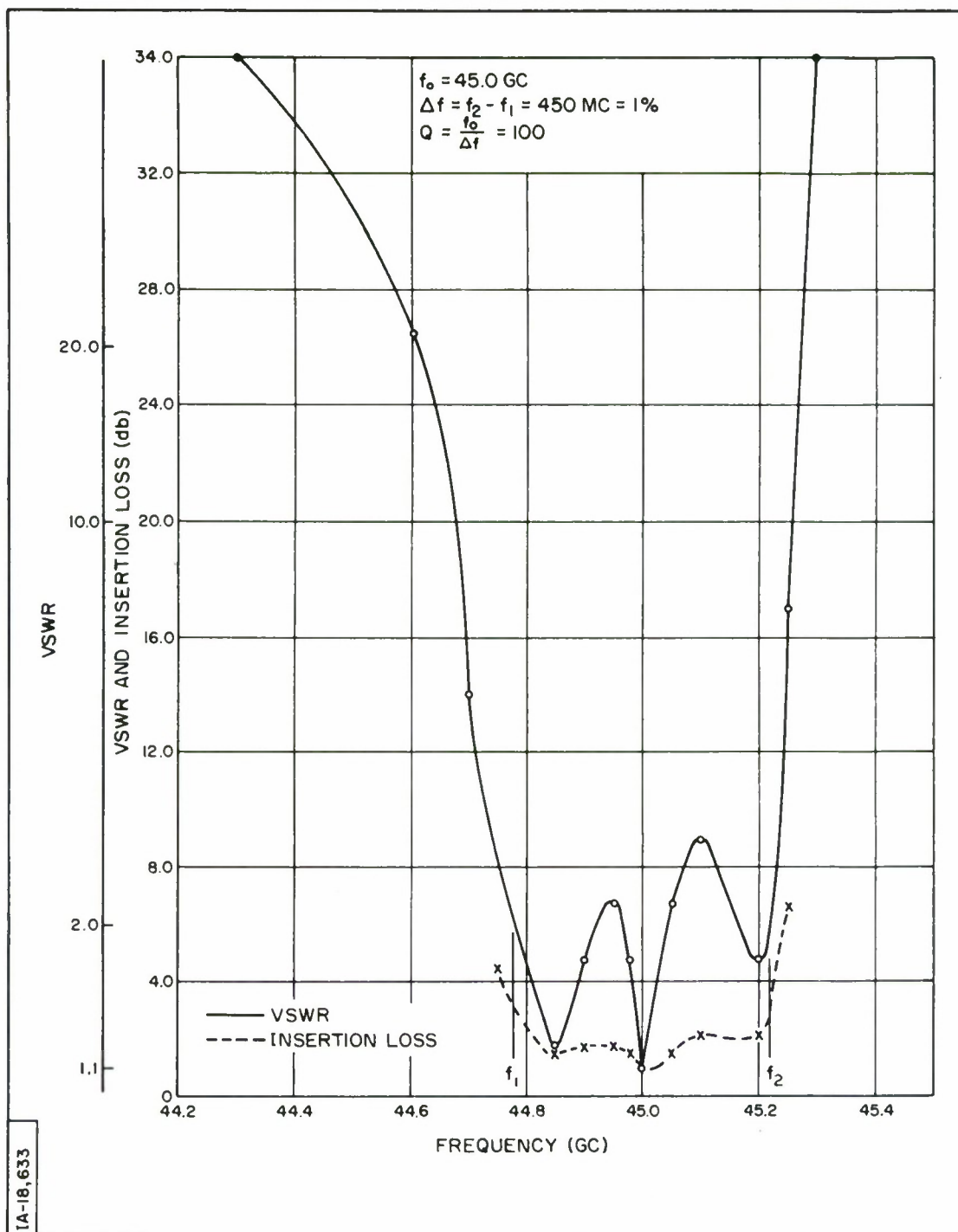


Figure 15. VSWR and Insertion Loss vs. Frequency of Q-Band Filter

receiver. The 90-Gc harmonic mixer (Figure 16) employs a 1N2792 diode, hermetically sealed in a section of RG-98/U waveguide. To maximize the IF signal, a 45-Gc filter is positioned on the local-oscillator side of the mixer, and an RG-98/U to WR-10 waveguide transition on the signal side of the harmonic mixer. The transition is a waveguide beyond cutoff for the LO signal and isolates the LO from the signal arm.

ANTENNA

The oxygen-lines-refractometer antenna system (Figure 17) is a casse-grain antenna with a 13-inch-diameter reflector having a 4-inch focal length. The subreflector is a 1.84-inch-diameter hyperbola. The feed horn is a double-ridge invar waveguide with a 0.04-inch x 0.3-inch aperture. Vertical linear polarization is used in this system. (See Table V for characteristics.)

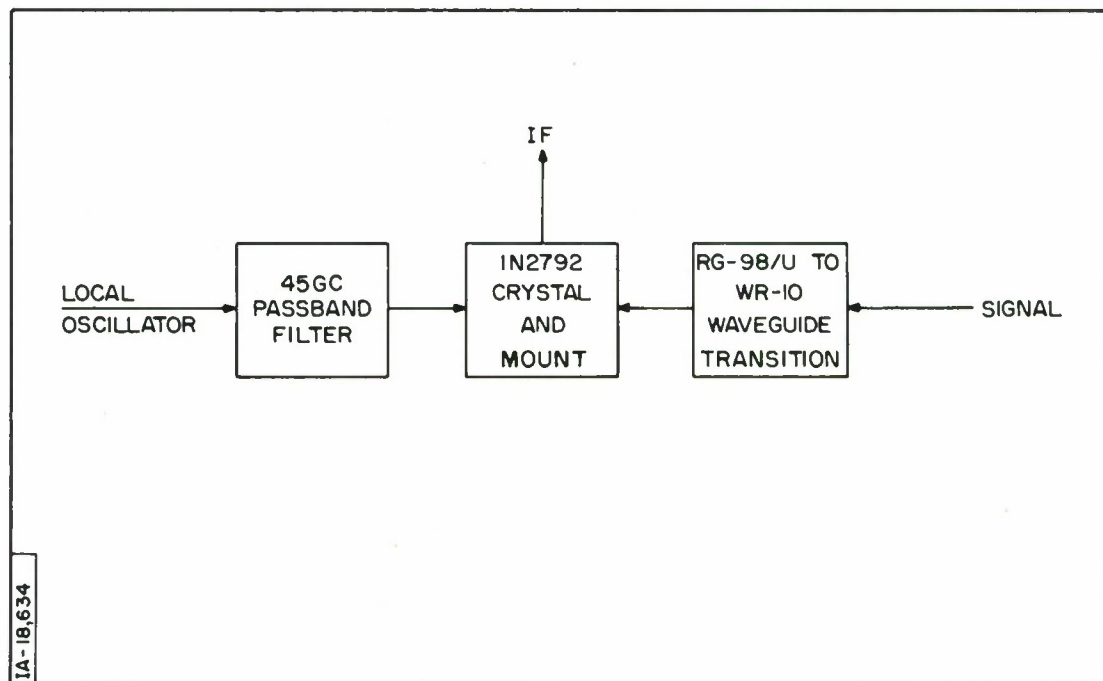


Figure 16. 90-Gc Harmonic Mixer Block Diagram

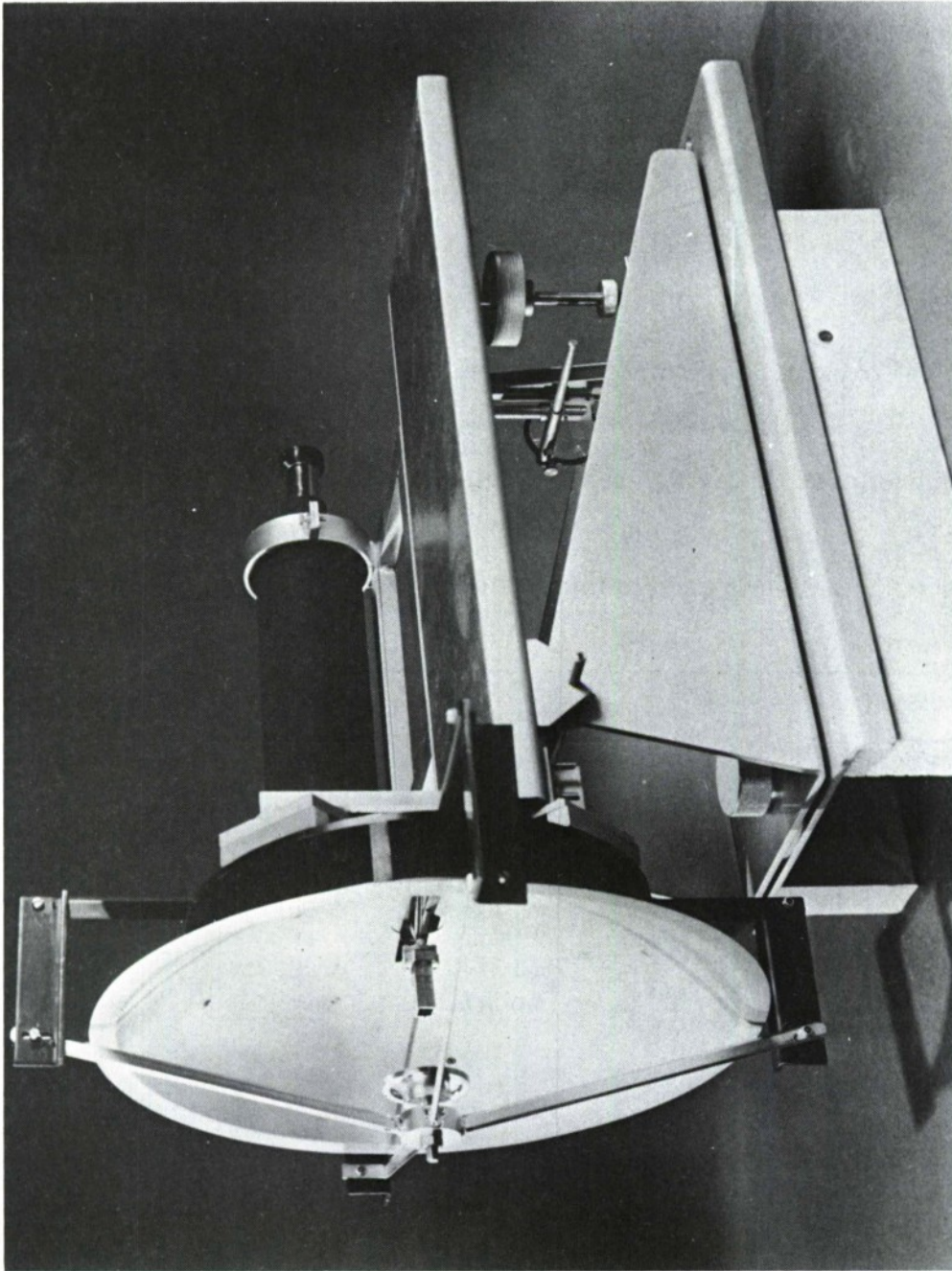


Figure 17. Cassegrain Antenna System

Table V
Characteristics of Antenna System

Frequency (Gc)	Beamwidth (deg)	Highest Sidelobe (db)	Measured Gain (db)
45	1.38 E&H	16.9 H-plane 17.5 E-plane	40
90	0.8 E&H	17.0 H-plane 16.0 E-plane	Not measured
Feedhorn beamwidth = 14° E- and H-planes			

The antenna radiation patterns are shown in Figures 18 through 21. Figure 18 is the E-plane radiation pattern at 45 Gc; Figure 19 is the H-plane, 45-Gc pattern; Figure 20 is the E-plane, 90-Gc radiation pattern; and Figure 21 is the H-plane, 90-Gc pattern.

OTHER MICROWAVE COMPONENTS

The rest of the microwave components shown in Figure 1, such as directional couplers, frequency meters, variable attenuators, and detectors, are standard, commercially available units.

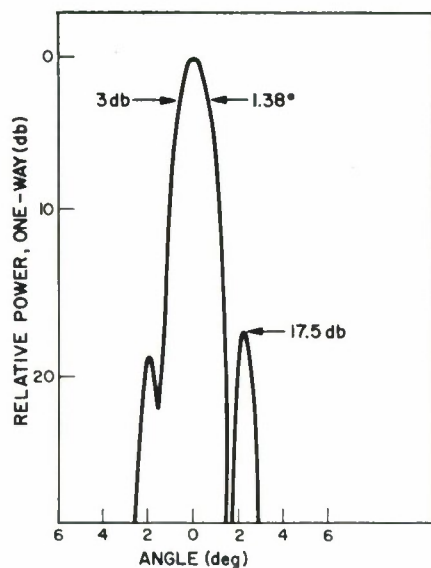


Figure 18. E-Plane Radiation Pattern of 13-inch-Diameter Cassegrain Antenna, 45 Gc

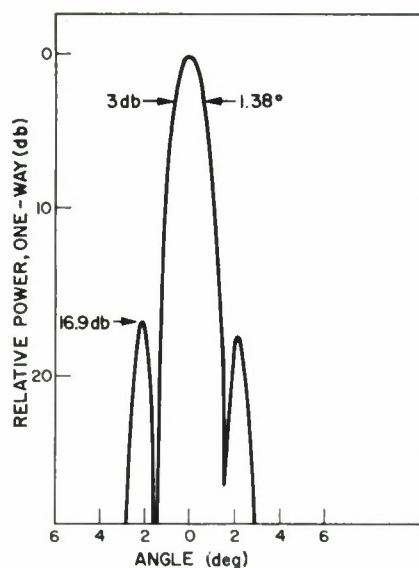


Figure 19. H-Plane Radiation Pattern of 13-inch-Diameter Cassegrain Antenna, 45 Gc

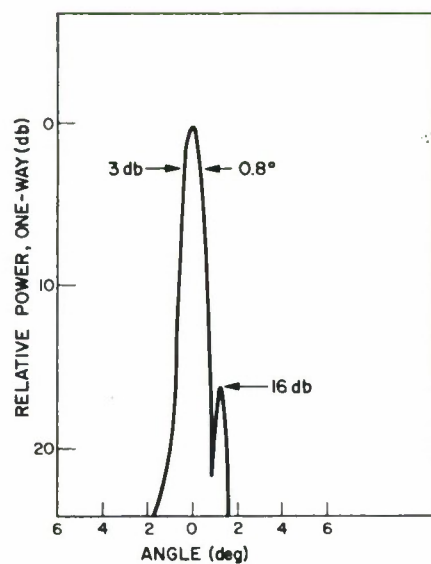


Figure 20. E-Plane Radiation Pattern of 13-inch-Diameter Cassegrain Antenna, 90 Gc

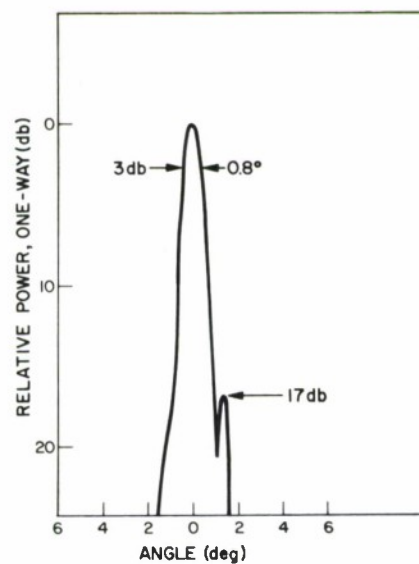


Figure 21. H-Plane Radiation Pattern of 13-inch-Diameter Cassegrain Antenna, 90 Gc

SECTION IV

PROBLEM AREAS

There are three major problem areas in the microwave portion of the oxygen-lines refractometer:

- (a) stability of the main-transmitter tube;
- (b) harmonic-generator efficiency; and
- (c) mixer sensitivity and noise.

STABILITY OF MAIN TRANSMITTER

The main-transmitter tube (an OKI laddertron) must be frequency- and power-stable. Output power is stabilized by operating the tube at or near the peak of the power-versus-cavity-voltage curve in Figure 4. Unwanted power fluctuations produce changes in the incident power of the harmonic generator which, in turn, produce amplitude and phase instabilities of the 90-Gc signal. The most severe tube-instability problem by far, is short-term frequency variation. Since the harmonic generator is, by virtue of its tuned elements, a very narrowband device, changes in the operating frequency result in very pronounced differential-phase changes measured at the phase comparator. Frequency stabilization of the laddertron was achieved by using two Dymec phase-lock oscillator synchronizers (see Figure 22) according to the technique described in a Dymec application-engineering note.^[9]

HARMONIC GENERATOR EFFICIENCY

In this system, the difficulty in obtaining sufficient power at 90 Gc was caused by the poor efficiency of the 45- to 90-Gc harmonic generator in the main transmitter, which, in turn, was caused by the nonavailability of varactor diodes with a high cutoff frequency (high Q).^[10]

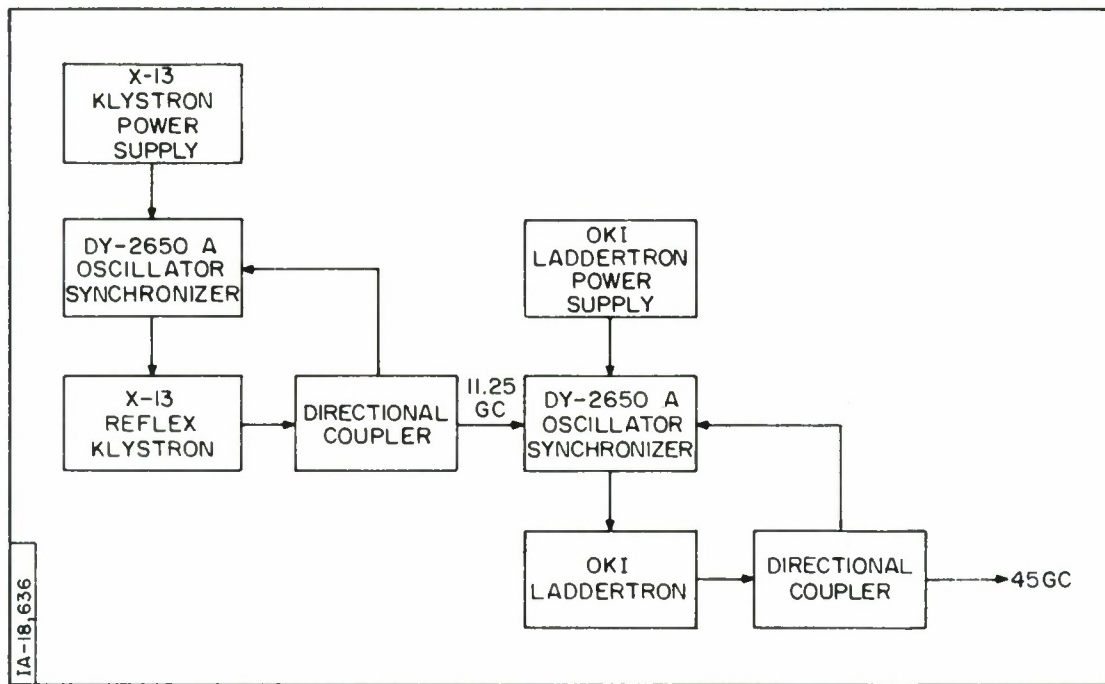


Figure 22. Block Diagram of Stabilized OKI Laddertron

MIXER SENSITIVITY AND NOISE

Improved crystal diodes and a diode holder designed specifically for 45 Gc will increase the 45-Gc-mixer tangential sensitivity. Local-oscillator noise can be reduced by balanced mixing instead of the single-ended mixing now used.

The tangential sensitivity of the 90-Gc mixer can be improved by reverting to fundamental mixing instead of harmonic mixing, but improved crystals and crystal holders for 90 Gc will be required for better performance. In addition, crystal noise can be improved by converting to balanced mixing and better impedance-matching at both RF and IF.

In short, the mixer problems are largely dependent upon the state-of-the-art in crystal and crystal-holder design.

SECTION V

STATUS AND CONCLUSIONS

DESIGN GOALS

The design goals established for the microwave portion of the line integral refractometer are listed below:

- (a) short-term phase stability, $\pm 0.5^{\circ}$;
- (b) long-term phase stability, $\pm 1.0^{\circ}$;
- (c) minimum 45-Gc power, 1 watt ;
- (d) minimum 90-Gc power, 10 mw .

TEST RESULTS

The microwave equipment described in this report has operated with limited success over a 23-km path (approximately 14 miles) at a field site in the Lake Winnepesaukee, New Hampshire, region. The measured available transmitted power is 3 watts at 45 Gc and 3 mw at 90 Gc. The low 90-Gc power is attributed to the poor 45- to 90-Gc harmonic-generator efficiency. The short-term differential-phase stability is $\pm 2^{\circ}$ RMS and the long-term phase stability is approximately $\pm 10^{\circ}$ RMS. This long-term phase stability is caused by many deficiencies in the microwave equipment, such as excessive ripple in the klystron power supplies, high noise figure of both the 45- and 90-Gc mixers (greater than 9 db), inability of the AFC to maintain long-term lock-on of the local oscillator to the main transmitter, and long-term power fluctuations of the main transmitter.

This long-term differential-phase stability, measured in an almost-constant atmosphere, proved inadequate for tracking slowly varying weather conditions.

The day-to-day resetability of the microwave receiver, using the reference transmitter, is approximately 50 degrees, but can be improved by phase-locking the reference-transmitter klystron to the LO klystron.

MODIFICATIONS TO IMPROVE PHASE STABILITY

Certain modifications in the microwave subsystem, listed below, might substantially improve the system phase stability.

- (1) Use a 90-Gc klystron instead of a 45- to 90-Gc harmonic generator for increased 90-Gc power (100-mw, 90-Gc klystrons are now available).
- (2) Phase-lock the 45- and 90-Gc klystrons to an ultrastable reference oscillator. Short-term frequency stabilities on the order of 10^{-8} can be achieved in this manner.
- (3) Increase the intermediate frequency to 60 Mc and use double frequency conversion to obtain the required 500 kc for phase measurements. This technique will reduce the $1/f$ noise of the mixers by approximately 6 db.

The performance data for the entire Line Integral Refractometer can be found in a MITRE document.^[11]

APPENDIX

HARMONIC GENERATOR EFFICIENCY

The efficiency of a varactor diode at a particular frequency is limited by its series resistance, R_s . The diode figure-of-merit, or cutoff frequency, f_c , is given by

$$f_c = \frac{1}{2\pi R_s C_{\min}} \quad , \quad (4)$$

where C_{\min} is the junction capacitance at the breakdown voltage of the varactor VB. Then, from Equation (4), as the cutoff frequency of a varactor increases (i. e. , R_s decreases), the efficiency of the harmonic generator using such a varactor also increases.

The power-handling capability of a varactor is determined by the C_{\min} ; the larger the C_{\min} , the greater the power-handling capacity. If, however, C_{\min} is large, then, from Equation (4), f_c is decreased and, hence, the efficiency of the harmonic generator is lowered.

Lee^[12] has calculated the maximum efficiency η_{\max} for the shunt-type frequency doubler:

$$\eta_{\max} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{1 + 2(f + f^2) + f^3} \quad , \quad (5)$$

where

$$f = 6\sqrt{3} \frac{f_o}{f_c} \quad ,$$

f_o = operating frequency .

A plot of η_{\max} as a function of f_c/f_o is shown in Figure 23.

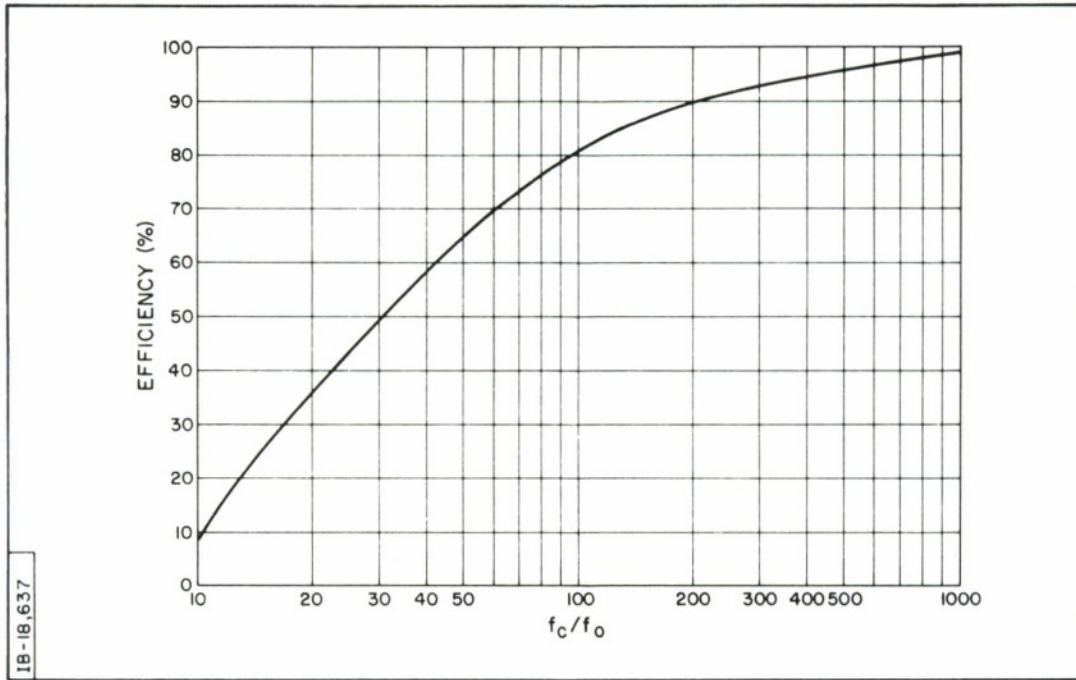


Figure 23. Maximum Efficiency vs. f_c/f_o of a Varactor Diode

For maximum efficiency, the maximum incident power P_{in} on an abrupt junction diode operating in the back-biased region is

$$P_{in} = 0.028 (\varphi + VB)^2 \omega_{in} C_{min}, \quad (6)$$

or,

$$P_{in} \propto C_{min} V^2,$$

where φ = contact potential and $V = \varphi + VB \approx VB$. Therefore, the input power and, hence, the power-handling capability, increases with the $C_{min} V^2$ product. The difference between input and output power equals the power dissipated in the varactor and its associated microwave circuitry. The power dissipation increases as the efficiency of the harmonic generator decreases. The manufacturer's rated (CW) power dissipation (at 10 Gc and 25°C ambient

temperature) for the varactors used in this system is 100 mw. Because of the poor efficiency obtained with these varactors at 45 Gc, most of the input power is lost in the circuit; hence, P_{in} must be kept in the 100- to 200-mw region. From Equation (3), then, the $C_{min} V^2$ product must be small; thus, the requirement for low capacitance at relatively low breakdown voltages. For example, assuming $P_{in} = 200$ mw and that 5-percent efficiency is required; input frequency is 45 Gc; and output frequency is 90 Gc, then, from Equation (6),

$$C_{min} (\phi + VB)^2 = \frac{35P_{in}}{\omega_{in}} \approx 25 \times 10^{-12} \text{ units of energy.}$$

The required value of $C_{min} = 0.05$ pf at $VB = -20$ volts, and, from Equation (2),

$$f_c \approx \frac{-20.8}{\eta - 1} f_o \approx 990 \text{ Gc.}$$

Cutoff frequencies in the vicinity of 1000 Gc at -20 volts are beyond the present state-of-the-art. A compromise had to be made in the selection of diodes for this application. Varactors were chosen for low capacitance at zero bias, breakdown voltages in the vicinity of -20 volts, and for as high a cutoff frequency as the state-of-the-art would allow.

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	ROLE	WT	ROLE	WT	ROLE	WT
Radar Dispersive Refractivity Oxygen-Lines Refractometer Dispersive Refractivity						

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